Part V
Ensuring Long-Term Protection

Chapter 11
Performing Closure and Post-Closure Care

Contents

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Performing Closure and Post-Closure Care

This chapter will help you:

- *Provide closure and post-closure care as an integral part of a unit's overall design and operation.*
- *Provide long-term environmental protection by reducing or eliminating potential threats and the need for potential corrective action at the site.*
- *Plan and accomplish the goals of closure and post-closure care by requiring that adequate funding be set aside to cover the planned costs of closure and post-closure care.*

The overall goal of closure is to minimize or eliminate potential threats to human health and the environment and the need for future corrective action at the site. If removing the wastes, containment devices, and any contaminated subsoils from a unit, the unit should be returned to an acceptable risk level so that it is not a current or future threat. If wastes will be left in place at closure, the unit should be closed in a manner that also reduces and controls current or future threats. Steps should also be taken to avoid future disruptions to final cover systems and monitoring devices.

This chapter will help address the following questions.

- How do I develop a closure plan?
- What factors should I consider when choosing a closure method?
- What are the components of a final cover?
- What costs are associated with post-closure care?

For post-closure care, the overall goal is to minimize the infiltration of water into a unit by providing maintenance of the final cover. Maintenance should be continued until such time as it is determined that care is no longer necessary. Also, during post-closure care, closed units should be monitored to verify and document that no unacceptable releases are occurring.

I. Closure Plans

A well-conceived closure plan is the primary resource document for the final stage in the life of a waste management unit. The purpose of a closure plan is to consider all aspects of the closure scenario. It should be comprehensive so that staff who will implement it years after its writing will clearly understand the activities it specifies. It also needs to provide enough detail to allow calculation of closure and post-closure care costs for determining how much funding needs to be set aside for those activities.

What should be considered when developing a closure plan?

You should tailor a closure plan to account for the unique characteristics of the unit, the waste managed in the unit, and anticipated future land use. Each unit will have different closure activities. Closing a surface impoundment, for example, involves removal of remaining liquids and solidifying sludges prior to placing a final cover on the unit.

The following information is important to consider when developing a closure plan:

- Overall goals and objectives of closure.
- Future land use.
- Type of waste management unit.
- Types, amount, and physical state of waste in the unit.
- Constituents associated with the wastes.
- Whether wastes will be removed or left in place at closure.
- Schedule (overall and interim).
- Costs to implement closure.
- Steps to monitor progress of closure actions, including inspections, maintenance, and monitoring (e.g., groundwater and leachate monitoring).
- Health and safety plans, as necessary.
- Contingency plans.
- Description of waste treatment or stabilization (if applicable).
- Final cover information (if applicable).
- Vegetation management.
- Run-on and runoff controls.
- Closure operations and maintenance.
- Erosion prevention and repair.
- Waste removal information (if applicable).
- Parameters to assess performance of the unit throughout the post-closure period.

The plan should address the types of waste that have been or are expected to be deposited in the management unit and the constituents that can reasonably be associated with those wastes. The types of expected wastes will affect both the design of the final cover and the types of activities that should be undertaken during the post-closure care period. Biodegradable waste, for example, can cause a final cover to subside due to decomposition and can also require gas management.

The closure plan should provide other information that will address the closure strategy. If, for instance, a final cover is planned, then the closure plan should consider seasonal precipitation that could influence the performance of both the cover and the monitoring system. Information concerning freeze cycles and the depth of frost permeation will provide supporting information with which to assess the adequacy of the cover design. Similarly, arid conditions should be addressed to support a decision to use a particular cover material, such as cobbles.

The closure plan should address the closure schedule, stating when closure is expected to begin, and when closure is expected to be completed. You should consider starting closure when the unit has reached capacity or has received the last expected waste for disposal. For units containing inorganic wastes, you should complete closure as soon as possible after the last expected waste has been received. A period of 180 days is a good general guide for completing closure, but the actual time frame will be dictated by site-specific conditions. For units receiving organic wastes, more time might be needed for the wastes to stabilize prior to completing closure. Similarly, other site-specific conditions, such as precipitation or winter weather, can also cause delay in completing closure. For these situations, you should complete closure as soon as feasible. You should also consult with the state agency to determine if any requirements exist for closure schedules.

Even within a waste management unit, some areas will be closed on different schedules, with certain areas in partial closure, while other areas continue to operate. The schedules and partial closure activities (such as intermediate cover) should be considered in the closure plan. Although the processes for closing such areas might not be different than those for closing the unit as a whole, it is still more efficient to integrate partial closure activities into the closure plan.

If the closure plan calls for the stabilization, solidification, or other treatment of wastes in the unit before the installation of a final cover, the plan should describe those activities in detail. Waste stabilization, solidification, or other treatment has four goals:

- Removing liquids, which are ill-suited to supporting the final cover.
- Decreasing the surface area over which the transfer or escape of contaminants can occur.
- Limiting the solubility of leachable constituents in the waste.
- Reducing toxicity of the waste.

For closure strategies that will use engineering controls, such as final covers, the plan should provide detailed specifications. This includes descriptions of the cover materials in each layer and their permeability as well as any drainage and/or gas migration control measures included in the operation of the final cover. Also the plan should identify measures to verify the continued integrity of the final cover and the proper operation of the gas migration and/or drainage control strategies.

If wastes will be removed at closure, the closure plan should estimate volumes of waste and contaminated subsoil and the extent of contaminated devices to be removed during closure. It should further state waste removal procedures, establish performance goals, and address any state or local requirements for closure by waste removal. The plan should identify numeric clean-up standards and existing background concentrations of constituents. It also should discuss the sampling plan for determining the effectiveness of closure activities. Finally, it should describe the provisions made for the disposal of removed wastes and other materials.

The closure plan should also provide a detailed description of the monitoring that will be conducted to assess the unit's performance throughout the post-closure period. These measurements include monitoring leachate volume and characteristics to ensure that a cover is minimizing infiltration. It is important to include appropriate ground-water quality standards with which to compare ground-water monitoring reports. You should develop the performance measures section of the plan prior to completing closure. This section establishes the parameters that will describe successful closure of the unit. If limits on these parameters are exceeded, it will provide an early warning that the final cover system is not functioning as designed and that measures should be undertaken to identify and correct problems.

II. Selecting a Closure Method

Factors to consider in deciding whether to perform closure by means of waste removal or through the use of a final cover include the following:

- **Feasibility.** Is closure by waste removal feasible? For example, if the waste volumes are large and underlying soil and ground water are contaminated, closure by total waste removal might not be possible. If the unit is contaminated, consult Chapter 10–Taking Corrective Action to identify activities to address the contamination. In some cases partial removal of the waste might be useful to remove the source of ground-water contamination.
- **Cost-effectiveness.** Compare the cost of removing waste, containment devices, and contaminated soils, plus subsequent disposal costs at another facility, to the cost of installing a final cover and providing post-closure care.
- **Long-term protection.** Will the final cover control, minimize, or eliminate post-closure escape of waste constituents or contaminated runoff to ground or surface waters to the extent necessary to protect human health and the environment?
- **Availability of alternate site.** Is an alternate site available for final disposal or treatment of removed waste? You should consult with the state agency to determine whether alternate disposal sites are appropriate.

Sections III and V address closure by use of final cover systems and associated post-closure care considerations. Alternatively, Section IV addresses closure by waste removal.

III. Closure by Use of Final Cover Systems

You might elect to close a waste management unit by means of a final cover system. This approach is common for landfill units and some surface impoundment units where some waste is left in place. The choice of final cover materials and design should be the result of a careful review and consideration of all site-specific conditions that will affect the performance of the cover system. If you are not knowledgeable about the engineering properties of cover materials, you should seek the advice of professionals or representatives of state and local environmental protection agencies.

This section addresses the more important technical issues that should be considered when selecting cover materials and designing a cover system. It discusses the various potential components of final cover systems, including the types of materials that can be used in their design and some of the advantages and disadvantages of each. This section also examines the interaction between the various components as they function within the system.

A. Purpose and Goal of Final Cover Systems

The principal goals of final cover systems are to:

- Provide long-term environmental protection of human health and the environment by reducing or eliminating potential risk of contaminant release.
- Minimize infiltration of precipitation into the waste management unit to minimize generation of leachates within the unit by promoting surface drainage and maximizing runoff.
- Minimize risk by controlling gas migration (as applicable), and by providing physical separation between waste and humans, plants, and animals.
- Minimize long-term maintenance needs.

The final cover should be designed to provide long-term protection and minimization of leachate formation. Final cover systems can be inspected, managed, and repaired to maintain long-term protection. For optimal performance, the final cover system should be designed to minimize infiltration, surface ponding, and the erosion of cover material. To avoid the accumulation of leachate within a unit, the cover system should be no more permeable than the liner system. For example, if a unit's bottom liner system is composed of a low-permeability material, such as compacted clay or a geomembrane, then the cover should also be composed of a low-permeability material unless an evaluation of site-specific conditions shows an equivalent reduction in infiltration. If the cover system is more permeable than the liner, leachate will accumulate in the unit. This buildup of liquids within a unit is often referred to as the "bathtub effect." In addition, since many units can potentially generate gas, cover systems should be designed to control gas migration. Proper quality assurance and quality control during construction and installation of the final cover are essential in order to ensure that the final cover performs in accordance with its design. For general information on quality assurance during construction of the final cover, refer back to the construction quality assurance section of Chapter 7, Section B–Designing and Installing Liners. Recommendations for the type of final cover system to use will depend on the type of liner and the gas and liquids management strategy employed in a unit.

B. Technical Considerations for Selecting Cover Materials

Several environmental and engineering concerns can affect cover materials and should be considered in the choice of those materials.

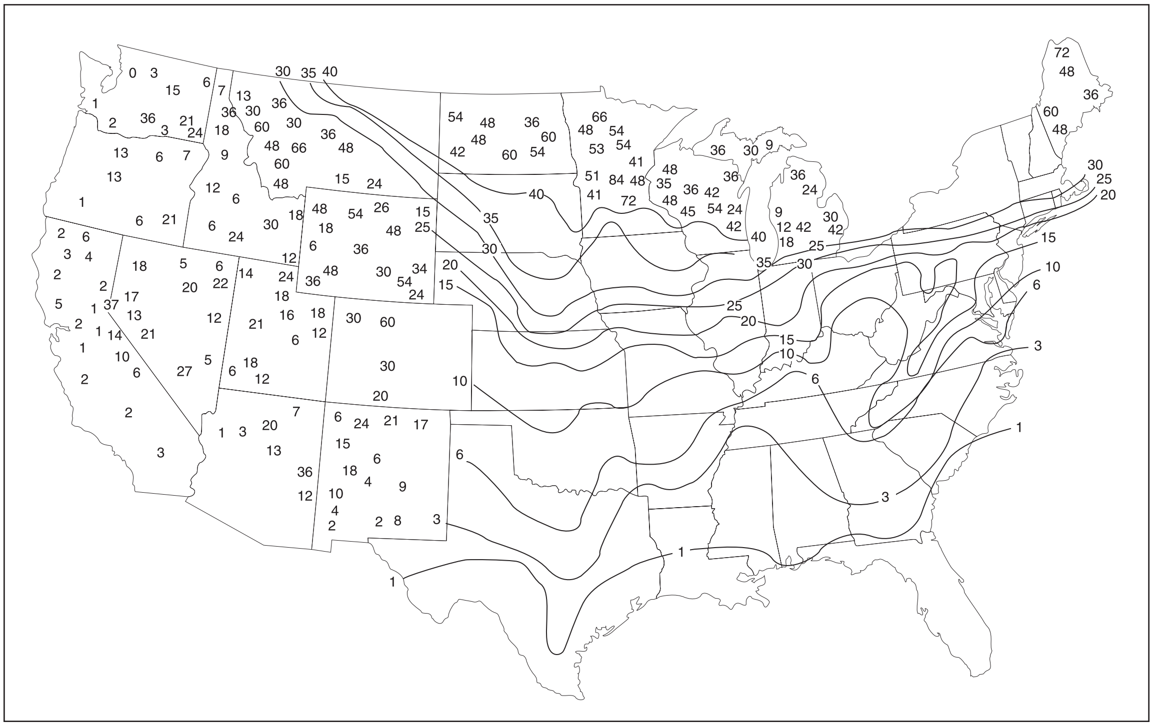
How can climate affect a final cover?

Freeze and thaw effects can lead to the development of microfractures in low permeability soil layers. These effects also can cause the realignment of interstitial fines (silts and clays), thereby increasing the hydraulic conductivity of the final cover. As a result, you should determine the maximum depth of frost penetration at a site and design covers accordingly. In other words, barrier layers should be below the maximum frost penetration depth. Information regarding the maximum frost penetration depth for a particular area can be obtained from the Natural Resource Conservation Service with the U.S. Department of Agriculture, local utilities, construction companies, local universities, or state agencies. Figure 1 illustrates the regional depth of frost penetration. You should ensure that vegetation layers are thick enough that low permeability soil layers in the final cover are placed below the maximum frost penetration depth.

How can settlement and subsidence affect a final cover?

When waste decomposes and consolidates, settlement and subsidence can result. Excessive settlement and subsidence can significantly impair the integrity of the final cover system by causing ponding of water on the surface, fracturing of low permeability infiltration layers, and failure of geomembranes. The degree and rate of waste settlement are difficult to estimate, but they should be considered during design and development of closure plans. Waste settlement should also be considered when determining the timing of closure. Steps should be taken to minimize the degree of settlement that will occur after the final cover system has been installed.

Figure 1. Regional Depth of Frost Penetration in Inches



Source: U.S. EPA, 1989a.

How can erosion affect the performance of a final cover?

Erosion can adversely affect the performance of the final cover of a unit by causing rills that require maintenance and repair. Extreme erosion can lead to the exposure of the infiltration layer, initiate or contribute to sliding failures, or expose the waste. Anticipated erosion due to surface-water runoff for a given design criteria can be approximated using the USDA Universal Soil Loss Equation[1] (U.S. EPA, 1989a). By evaluating erosion loss, you might be able to optimize the final cover design to reduce maintenance through selection of the best available soil materials. A vegetative cover not only improves the appearance of a unit, but it also controls erosion of the final cover.

The vegetation components of the erosion layer should have the following characteristics:

- Locally adapted perennial plants that are resistant to various climatic changes reasonably expected to occur at the site.
- Roots that will not disrupt the low-permeability layer.
- The ability to thrive in low-nutrient soil with minimum nutrient addition.
- The ability to survive and function with little or no maintenance.

Why are interfacial and internal friction properties for cover components important?

Adequate friction between cover components, such as geomembrane barrier layers and soil drainage layers, as well as between any geosynthetic components, is needed to prevent extensive slippage or interfacial shear. Water and ice can affect the potential for

[1] USDA Universal Soil Loss Equation: X = RKLSCP where: X = Soil loss (tons/acre/year); R = Rainfall erosion index; K = Soil erodibility index; L = Slope length factor; S = Slope gradient factor; C = Crop management factor; P = Erosion control practice. For minimal long-term care X < 2.0 tons/acre/year.

cover components to slip. Sudden sliding can tear geomembranes or cause sloughing of earthen materials. Internal shear can also be a concern for composite or geosynthetic clay liner materials. Measures to improve stability include using flatter slopes or textured geosynthetic membranes, geogrids designed to resist slipping forces, otherwise reinforcing the cover soil, and providing drainage.

Can dry soil materials affect a final cover?

Desiccation, the natural drying of soil materials, can have an adverse affect on the soil layers compromising the final cover. Although this process is most commonly associated with layers of low permeability soil, such as clay, it can cause problems with other soil types as well. Desiccation causes cracks in the soil surface extending downward. Cover layers are not very thick, and therefore these cracks can extend through an entire layer, radically changing its hydraulic conductivity or permeability. Care should be taken to detect desiccation at an early stage in time to mitigate its damage. Also, the tendency for final covers to become dry makes root penetration even more of a problem in that plants respond to drought by extending their root systems downward.

Can plants and animals have an effect on a final cover?

When selecting the plant species to include in the vegetative cover of a waste management unit, you should consider the potential for root systems to grow through surface cover layers and penetrate underlying drainage and barrier layers. Such penetration will form preferential pathways for water infiltration and compromise the integrity of the final cover system. Similarly, the presence of burrowing animals should be foreseen when designing the final cover system. Such animals can burrow in the surface layers and can potentially breach the underlying barrier layer. Strategies for mitigating the effects described here are discussed below in the context of protection layers composed of gravel or cobbles.

Is it necessary to stabilize wastes?

Before installing a final cover, liquid or semi-liquid wastes might need to be stabilized or solidified. Stabilization or solidification might be necessary to allow equipment on the unit to install the final cover or to ensure adequate support, or bearing capacity, for the final cover. With proper bulk cover technique, it might be feasible to place the cover over a homogeneous, gel-like, semi-liquid waste. When selecting a stabilization or solidification process, it is important to consider the effectiveness of the process and its compatibility with the wastes. Performance specifications for stabilization or solidification processes include leachability, free-liquid content, physical stability, bearing capacity, reactivity, ignitability, biodegradability, strength, permeability, and durability of the stabilized and solidified waste. You should consider seeking professional assistance to properly stabilize or solidify waste prior to closure.

Where solidification is not practical, you should consider reinforcement and construction of a specialized lighter weight cover system over unstable wastes. This involves using combinations of geogrids, geotextiles, geonets, geosynthetic clay liners, and geomembranes. For more detail on this practice, consult references such as the paper by Robert P. Grefe, *Closure of Papermill Sludge Lagoons Using Geosynthetics and Subsequent Performance*, and the Geosynthetic Research Institute proceedings, *Landfill Closures: Geosynthetics Interface Friction and New Developments*, cited in the Resources section.

How can wastes be stabilized?

Many stabilization and solidification processes require the mixing of waste with other materials, such as clay, lime, and ash. These processes include either sorbents or encapsulating agents. Sorbents are nonreactive and nonbiodegradable materials that soak up free liquids to form a solid or near-solid mass. Encapsulating agents enclose wastes to form an impermeable mass. The following are examples of some commonly used types of waste stabilization and solidification methods.

- **Cement-based techniques.** Portland cement can use moisture from the waste (sludge) for cement hydration. The end product has high strength, good durability, and retains waste effectively.
- **Fly ash or lime techniques.** A combination of pozzolanic fly ash, lime, and moisture can form compounds that have cement-like properties.
- **Thermoplastic techniques.** Asphalt, tar, polyolefins, and epoxies can be mixed with waste, forming a semi-rigid solid after cooling.
- **Organic polymer processes.** This technique involves adding and mixing monomer with a sludge, followed by adding a polymerizing catalyst. This technique entraps the solid particles.

After evaluating and selecting a stabilization or solidification process, you should conduct pilot-scale tests to address issues such as safety, mix ratios, mix times, and pumping problems. Testing will help assess the potential for an increase in waste volume. It will also help to plan the production phase, train operators, and devise construction specifications.

When conducting full-scale treatment operations, options exist for adding and mixing materials. These options might include in situ mixing and mobile plant mixing. In situ mixing is the simplest technique, using common construction equipment, such as backhoes, excavators, and dump trucks. In situ mixing is most suitable where large amounts of materials are added to stabilize or solidify the waste. The existing waste management area, such as a surface impoundment, can be used as the mixing area. The in situ mixing process is open to the atmosphere, so environmental and safety issues, such as odor, dust, and vapor generation, should be taken into consideration. For mobile plant mixing, wastes are removed from the unit, mechanically mixed with treatment materials in a portable processing vessel, and deposited back into the unit. Mobile plant mixing is generally used for treating sludges and other wastes with a high liquid content.

C. Components of a Final Cover

Cover systems can be designed in a variety of ways to accomplish closure goals. This flexibility allows a final cover design system to integrate site-specific technical considerations that can affect performance. This section discusses the potential components or layers of a final cover system, their functions, and appropriate materials for each layer. Since the materials used in cover systems are the same as those used in liner systems, refer to Chapter 7, Section B–Designing and Installing Liners for a more detailed discussion of the engineering properties of the various materials.

Table 1 presents the types of layers and typical materials that might exist in a final cover. The minimum appropriate thicknesses of each of the five types of layers depends upon many factors including site drainage, erosion potential, slopes, types of vegetative cover, type of soil, and climate.

Table 1
Types of Layers in Final Cover Systems

Layer	Type of Layer	Typical Materials
1	Surface (Erosion, Vegetative Cover) Layer	Topsoil, Geosynthetic Erosion Control Layer, Cobbles
2	Protection Layer	Soil, Recycled or Reused Waste Materials, Cobbles
3	Drainage Layer	Sand and/or Gravel, Geonet or Geocomposite, Chipped or Shredded Tires
4	Barrier (Infiltration) Layer	Compacted Clay, Geomembrane, Geosynthetic Clay Liner
5	Foundation/Gas Collection Layer	Sand or Gravel, Soil, Geonet or Geotextile, Recycled or Reused Waste Material

Source: Jesionek *et al.*, 1995

What function does the surface layer serve?

The role of the surface layer in the final cover system is to promote the growth of native, non-woody plant species, minimize erosion, restore the aesthetics of the site, and protect the barrier layer. The surface layer should be thick enough so that the root systems of the plants do not penetrate the underlying barrier layer. The vegetation on the surface layer should be resistant to drought and temperature extremes, able to survive and function with little maintenance, and also be able to maximize evapotranspiration, which will limit water infiltration to the barrier layer. It is recommended that you consult with agriculture or soil conservation experts concerning appropriate cover vegetation. Finally, the surface layer should be thick enough to withstand long-term erosion and to prevent desiccation and freeze/thaw effects of the barrier layer. The recommended minimum thickness for the surface layer is at least 12 inches. The state agency can help to determine the appropriate minimum thickness in cold climates to protect against freeze-thaw effects.

What types of materials can be used in the surface layer?

Topsoil has been by far the most commonly used material for surface layers. The principal advantages of using topsoil in the surface layer include its general availability and its suitability for sustaining vegetation. When topsoil is used as a surface layer, the roots of plants will reinforce the soil, reduce the rate of erosion, decrease runoff, and remove water from the soil through evapotranspiration. To achieve these benefits, however, the soil should have sufficient water-holding capacity to sustain plant growth. There are some concerns with regard to using topsoil. For example, topsoil requires ongoing maintenance, especially during periods of drought or heavy rainfall. Prolonged drought can lead to cracking in the soil, creating preferential pathways for water infiltration. Heavy rainfall can lead to erosion causing rills or gullies, especially on newly-seeded or steeply sloping covers. If the topsoil does not have sufficient water holding capacity, it can not adequately support surface plant growth, and evapotranspiration can excessively dry the soils. In this case, irrigation will be required to restore the water balance within the soil structure. Topsoil is also vulnerable to penetration by burrowing animals.

Geosynthetic erosion control material can be used as a cover above the topsoil to limit erosion prior to the establishment of a mature vegetative cover. The geosynthetic material can include embedded seeds to promote plant growth, and can be anchored or reinforced to add stability on steeply sloped areas. Geosynthetic material, however, does not enhance the water-holding capacity of the soil. In arid or semi-arid areas, therefore, the soil might still be prone to wind and water erosion if its water-holding capacity is insufficient.

Cobbles can be a suitable material for the surface layer in arid areas or on steep slopes which might hinder the establishment of vegetation. If they are large enough they will provide protection from wind and water erosion without washout. Cobbles can also protect the underlying barrier layer from intrusion by burrowing animals, but cobbles might not be available locally, and their use does not protect the underlying barrier layer from water infiltration. Because cobbles create a porous surface through which water can percolate, they do not ordinarily support vegetation. Wind-blown soil material can fill voids between cobbles, and plants can establish themselves in these materials. This plant material should be removed, as its roots are likely to extend into the underlying barrier layer in search of water.

What function does the protection or biotic barrier layer serve?

A protection or biotic barrier layer can be added below the surface layer, but above the drainage layer, to protect the latter from intrusion by plant roots or burrowing animals. This layer adds depth to the surface layer, increasing its water storage capacity and protecting underlying layers from freezing and erosion. In many cases, the protection layer and the surface layer are combined to form a single cover layer.

What types of materials can be used in the protection layer?

Soil will generally be the most suitable material for this layer, except in cases where special design requirements exist for the protection layer. The advantages and disadvantages of using soil in the protection layer are the same as those stated above in the discussion of the surface layer topsoil. Factors impacting the thickness and type of soil to use as a protection layer include freeze and thaw properties and the interaction between the soil and drainage layers. Other types of materials that can be used in the protection layer include cobbles with a geotextile filter, gravel and rock, and recycled or reused waste.

Cobbles with a geotextile filter can form a good barrier against penetration by plant roots and burrowing animals in arid sites. The primary disadvantage is that cobbles have no water storage capacity and allow water percolation into underlying layers.

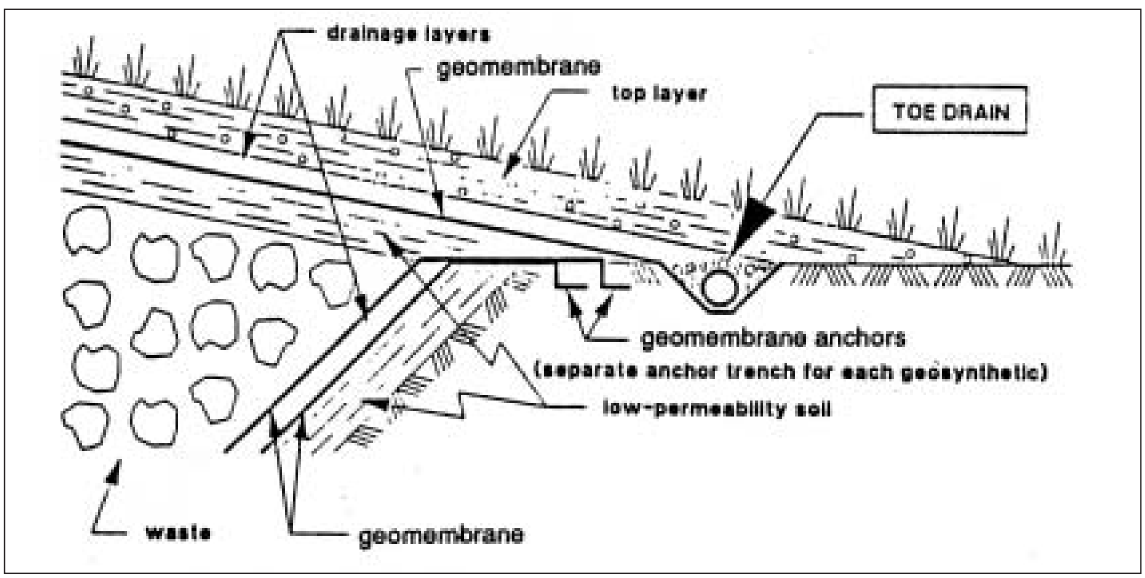
Gravel and rock are similar to cobbles since they can form a good barrier against penetration by plant roots and burrowing animals. Again, this use is usually only considered for arid sites, because gravel and rocks have no water storage capacity and allow water percolation into underlying layers.

Recycled or reused waste materials such as fly ash and bottom ash can be used in the protection layer, when available. Check with the state agency to verify that use of these materials is allowable. The advantages of using these materials in the protection layer are that they store water that has infiltrated past the surface layer, which can then be returned to the surface through evapotranspiration, and that they offer protection against burrowing animals and penetration by roots. If planning to use waste material in the protection layer, consider its impact on surface runoff at the unit's perimeter. Design controls to ensure runoff does not contribute to surface-water contamination. Consult Chapter 6–Protecting Surface Water for more details on designing runoff controls.

What function does the drainage layer serve?

A drainage layer can be placed below the surface layer, but above the barrier layer, to direct infiltrating water to drainage systems at the toe of the cover (see Figure 2) or to intermittent benches on long steep slopes. For drainage layers, the thickness will depend on the level of performance being designed and the properties of available materials. For example, some geonet composites, with a thickness of less than 1 inch, have a transmissivity equal to a much thicker layer of aggregate or sand. The recommended thickness of the high permeability soil drainage layer is 12 inches with at least a 3 percent slope at the bottom of the layer. Based on standard practice, the drainage layer should have a hydraulic conductivity in the range of 10^{-2} to 10^{-3} cm/sec. Water infiltration control through a drainage layer improves slope stability by reducing the duration of surface and protection layer saturation. In this role, the drainage layer works with vegetation to remove infiltrating water from the cover and protect the underlying barrier layer. If this layer drains the overlying soils too well, it could lead to the need for irrigation of the surface layer to avoid desiccation.

Figure 2. Drainage Layer Configuration



Source: U.S. EPA, 1991.

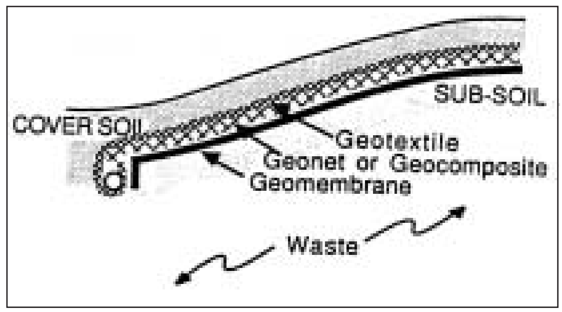
Another consideration for design of drainage layers is that the water should discharge freely from the toe of the cover or intermittent benches. If outlets become plugged or are not of adequate capacity, the toe of the slope can become saturated and potentially unstable. In addition, when designing the drainage layer, you should consider using flexible corrugated piping in conjunction with either the sand and gravel or the gravel with geotextile filter material to facilitate the movement of water to the unit perimeter.

What materials can be used in the drainage layer?

Sand and gravel are a common set of materials used in the drainage layer. The principal consideration in their use is the hydraulic conductivity required by the overall design. There can be cases in which the design requires the drainage of a large amount of water from the surface layer, and the hydraulic properties of the sand and gravel layer might be insufficient to meet these requirements. The advantages of using sand and gravel in the drainage layer include the ability to protect the underlying barrier layer from intrusion, puncture, and temperature extremes. The principal disadvantage to these materials is that they are subject to intrusions from the overlying protective layer that can alter their hydraulic conductivity. Similarly, fines in the sand and gravel can migrate downslope, undermining the stability of the cover slope. A graded filter or a geotextile filter can be used to separate and protect the sand and gravel from intrusions by the overlying protection layer.

Gravel with a geotextile filter is also a widely-used design, whose applicability can be limited by the local availability of materials. The gravel promotes drainage of water from the overlying layers, while the geotextile filter prevents the clogging of granular drainage layers. Again, be aware of the possibility that a gravel drainage layer might drain overlying soils so well that irrigation of the surface layer might become necessary. The principal advantage to a gravel/geotextile drainage layer is the engineering community's considerable body of knowledge regarding their use as drainage materials. Other advantages include their ability to protect underlying layers from intrusion, puncture, temperature extremes, and their common availability. The geotextile filter provides a cushion layer between the gravel and the overlying protection layer.

Figure 3.
Geonet with Geotextile Filter Design for Drainage Layer



Source: U.S. EPA, 1991.

Geonet and geotextile filter materials can be used to form an effective drainage layer directly above a compacted clay or geomembrane liner (see Figure 3). They are a suitable alternative especially in cases where other materials, such as sand and gravel, are not locally available. The principal advantage is that lightweight equipment can be used during installation, reducing the risk of damaging the underlying barrier layer.

The disadvantages associated with geonet and geotextile materials are that they provide little protection for the barrier layer against extreme temperature changes, and there can be slippage between the interfaces between the geomembrane, geotextile, and low permeability soil barrier materials. The use of textured materials can be considered to address slippage. Furthermore, problems can arise in the horizontal seaming of the geotextile drainage layer on long slopes.

Chipped or shredded tires are an additional option for drainage layer materials. Chipped or shredded tires have been used for bottom drainage layers in the past and might be suitable for cover drainage layers as well. One caution concerning the use of chipped or shredded tires is possible metal contaminants, or pieces of metal that could damage a geomembrane liner. You should consult with the state agency to determine whether this option is an acceptable practice.

What function does the barrier layer serve?

The barrier layer is the most critical component of the cover system because it prevents water infiltration into the waste. It also indirectly promotes the storage and drainage of water from the overlying protection and surface layers, and it prevents the upward movement of gases. This layer will be the least permeable component of the final cover system. Typically, the hydraulic conductivity of a barrier layer is between 10^{-9} to 10^{-7} cm/sec.

What types of materials can be used in the barrier layer?

Single compacted clay liners (CCLs) are the most common material used as barrier layers in final cover systems. CCL popularity arises largely because of the local availability of materials and the engineering community's extensive experience with their use. Drying and subsidence are the primary difficulties posed by CCLs. When the clay dries, cracks appear and provide preferential pathways along which water can enter the waste, promoting leachate formation, waste decomposition, and gas formation (when methane producing waste is present). Dry waste material and gas formation within the unit contribute to drying from below, while a range of climatological conditions, including drought, can affect CCLs from above. Even with extremely thick surface and protection layers, CCLs can still undergo some desiccation.

Clay liners are also vulnerable to subsidence within the waste unit. This problem can first manifest itself during liner construction. As the clay is compacted with machinery, the waste might not provide a stable, even foundation for the compaction process. This will make it difficult to create the evenly measured lifts comprising the liner. As waste settles over time, depressions can form along the top of the CCL. These depressions put differential stresses on the liner, causing cracks which compromise its integrity. For instance, a depression of only 5 to 11 inches across a 6-foot area can be sufficient to crack the liner materials.

Single geomembrane liners are sheets of a plastic polymer combined with other ingredients to form an effective barrier to water infiltration. Such liners are simple and straightforward to install, but they are relatively fragile and can be easily punctured during installation or by movement in surface layer materials. The principal advantage of a geomembrane is that it provides a relatively impermeable barrier with materials that are generally available. It is not damaged by temperature extremes and therefore does not require a thick surface layer. The geomembrane is more flexible than clay and not as vulnerable to cracking as a result of subsidence within the unit. The principal disadvantage is that it provides a point of potential slippage at the interface with the cover soils. Such slippage can tear the geomembrane, even if it is anchored.

Single geosynthetic clay liners (GCLs) are composed of bentonite clay supported by geotextiles or geomembranes held together with stitching or adhesives. These liners are relatively easy to install and have some self-healing capacity for minor punctures. They are easily repaired by patching. The main disadvantages include low shear strength, low bearing capacity, vulnerability to puncture due to relative thinness, and potential for slippage at interfaces with under- and overlying soil materials. When dry, their permeability to gas makes GCLs unsuitable as a barrier layer for wastes that produce gas, unless the clay will be maintained in a wet state for the entire post-closure period.

Geomembrane with compacted clay liners (CCLs) can be used to mitigate the shortcomings of each material when used alone. In this composite liner, the geomembrane acts to protect the clay from desiccation, while providing increased tolerance to differential settlement within the waste. The clay acts to protect the geomembrane from punctures and tearing. Both components act as an effective barrier to water infiltration. The principal disadvantage is slippage between the geomembrane and surface layer materials.

Geomembrane with geosynthetic clay liners (GCLs) can also be used as a barrier layer. As with geomembrane and CCL combinations, each component serves to mitigate the weakness of the other. The geosynthetic material is less vulnerable than its clay counterpart to cracking and has a moderate capacity to self-heal. The geomembrane combined with the GCL is a more flexible cover and is less vulnerable to differential stresses from waste settlement. Neither component is readily affected by extreme temperature changes, and both work together to form an effective barrier layer. For more information on the properties of geosynthetic clay liners, including their hydration after installation, refer to Chapter 7, Section B–Designing and Installing Liners. The potential disadvantage is slippage between the upper and lower surfaces of the geomembrane and some types of GCL and other surface layer materials. The geomembrane is still vulnerable to puncture, so placement of cover soils is important to minimize such damage.

Textured geomembranes can be used to increase the stability of cap side slopes. Textured geomembranes are nearly identical to standard “smooth” geomembranes differing only in the rough or textured surface that has been added. This textured surface increases the friction between the liner and soils and other geosynthetics used in the cap, and can help prevent sliding failures. In general, textured geomembranes are more expensive than comparable “smooth” geomembranes.

Using textured geomembranes allows cap designers to employ steeper slopes which can increase the available airspace in a waste management unit, and therefore increase its capacity. Textured geomembranes also help keep cover soil in place improving overall liner stability on steep slopes. The degree to which textured geomembranes will improve frictional resistance (friction coefficients/friction angles) will vary from site-to-site depending upon the type of soil at the site and its condition (e.g., moisture content).

Textured geomembranes are manufactured by two primary methods. Some textured geomembranes have a friction coating layer added to standard “smooth” geomembranes through a secondary process. Others are textured during the initial production process, meaning textured layers are coextruded as part of the liner itself. Textured geomembranes can be textured on one or both sides.

Textured geomembranes are seam-welded by the same technologies as standard geomembranes. Due to their textured surface, however, seam welds can be less uniform with textured liners than with normal liners. Some textured geomembranes have smooth edges on the top and bottom of the sheet to allow for more uniform seam welding.

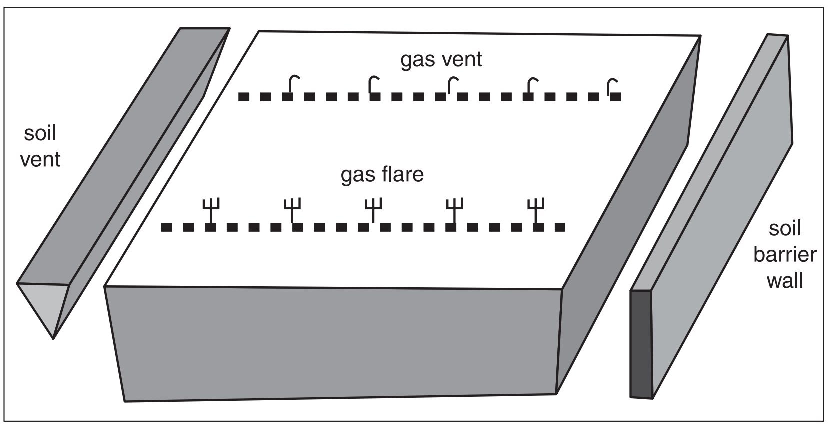
What function does the gas collection layer serve?

The role of the gas collection layer is to control the migration of gases to collection vents. This collection layer is a permeable layer that is placed above the foundation layer. It is often used in cases where the foundation layer itself is not the gas collection layer. For more information on Clean Air Act requirements for managing gas from landfills and other waste management units, refer to Chapter 5–Protecting Air Quality.

Gas control systems generally include mechanisms designed to control gas migration and to help vent gas emissions into the atmosphere. Systems using natural pressure and convection mechanisms are referred to as passive gas control systems (see Figure 4). Examples of passive gas control system elements include ditches, trenches, vent walls, perforated pipes surrounded by coarse soil, synthetic membranes, and high moisture, fine-grained soil. Systems using mechanical means to remove gas from the unit are referred to as active gas control systems. Figure 5 illustrates an active gas system. Gas control systems can also be used as part of corrective action measures should the concentration of methane rise to dangerous levels. As with all aspects of a waste containment system, construction quality assurance plays a critical role in the success of a gas management system.

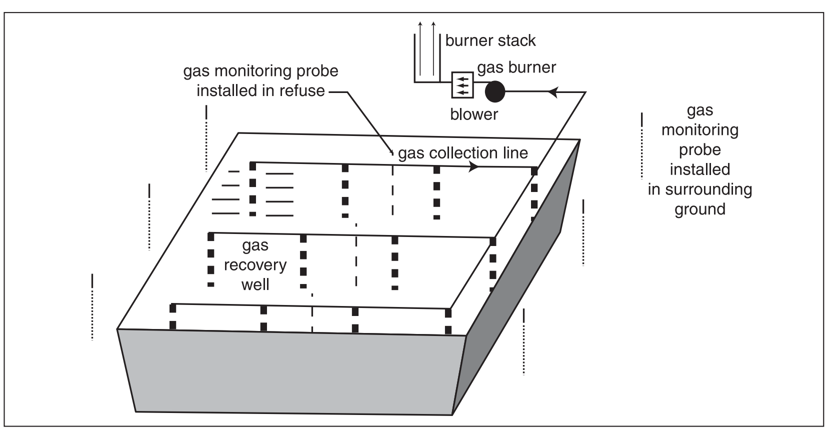
Gas extraction wells are an example of active gas control systems. For deep wells, the number, location, and extent of the pipe perforations are important. Also, the depth of the well must be kept safely above the liner system beneath the waste. For continuous gas

Figure 4. Passive Gas Venting System



Source: Robinson, W., ed. 1986. *The Solid Waste Handbook: A Practical Guide*. Reprinted by permission of John Wiley & Sons, Inc.

Figure 5. Active Gas Venting System



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collection layers beneath the barrier layer, continuity is important for both soils and geosynthetics.

Knowing the rate of gas generation is essential to determining the quantity of gas that can be extracted from the site. Pumping an individual well at a greater vacuum will give it a wider zone of influence, which is acceptable, but obviously there are points of diminishing marginal returns. Larger suction pressures influence a larger region but involve more energy expended in the pumping. Pumping at greater vacuum also increases the potential for drawing in atmospheric air if the pumping rate is set too high. Significant air intrusion into the unit can result in elevated temperatures and even underground fires. You should perform routine checks of gas generation rates to better ensure that optimal pumping rates are used.

The performance of gas extraction systems is affected by the following parameters, which should be considered when designing and operating gas systems:

- Daily cover, which inhibits free movement of gas.
- Sludge or liquid wastes, which affect the ease at which gas will move.
- Shallow depth of unit, which makes it difficult to extract the gas, because atmospheric air will be drawn in during the pumping.
- Permeability of the final cover, which affects the ability of atmospheric air to permeate the wastes in the unit.

What types of materials can be used in the gas collection layer?

Sand and gravel are the most common materials used for gas collection layers. With these materials, a filter might be needed to prevent infiltration of materials from the barrier layer. Geotextile and geosynthetic drainage composites also can make suitable gas collection layers. In many cases, these can be the most cost-effective alternatives. The same disadvantages exist with these materials in the gas collection layer as in other layers, such as slippage and continuity of flow.

With a geomembrane in the final cover barrier system, uplift pressures will be exerted unless the gas is quickly and efficiently conveyed to the wells, vents, or collection trenches. If this is not properly managed, uplift pressure will either cause bubbles to occur, displacing the cover soil and appearing at the surface, or decrease the normal stress between the geomembrane and its underlying material. This problem has led to slippage of the geomembrane and all overlying materials creating high tensile stresses evidenced by folding at the toe of the slope and tension cracks near the top.

D. Capillary-Break Final Covers

The capillary-break (CB) approach is an alternative design for a final cover system (see Figure 6). This system relies on the fact that for adjacent layers of fine- and coarse-textured material to be in water-potential equilibrium, the coarse-grained material (such as crushed stone) will tend to have a much lower water content than the fine-grained material (such as sand). Because the conductivity of water through a soil decreases exponentially with its water content, as a soil becomes more dry, its tendency to stay dry increases. Therefore, as long as the strata in a capillary break remain unsaturated (remain above the water table), the overlying fine-textured soil will retain nearly all the water and the coarse soil will behave as a barrier to water percolation due to its dryness. Since this phenomenon breaks down if the coarse layer becomes saturated, this alternative cover system is most appropriate for semiarid and desert environments.

What types of materials are used in capillary-break covers?

The CB cover system typically consists of five layers: surface, storage, capillary-break, barrier, and foundation. The surface, barrier, and foundation layers play the same role in the cover system as described above. The storage layer consists of fine material, such as silty sand. The capillary-break, or coarse, layer consists of granular materials, such as gravel and coarse sand. A fabric filter is often placed between the coarse and fine layers.

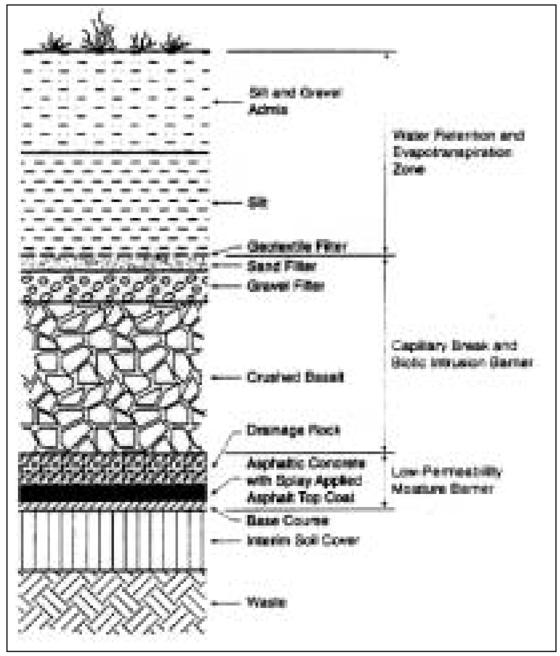
E. The Hydrologic Evaluation of Landfill Performance (HELP) Model

The relative performance of various cover designs can be evaluated with the Hydrologic Evaluation of Landfill Performance (HELP) model, developed by the U.S. Army Corps of Engineers Waterway Experiment Station for EPA. The HELP model was designed specifically to support permit writers and engineers in evaluating alternative landfill designs, but it can also be used to evaluate various final cover designs.

The HELP model integrates runoff, percolation, and subsurface-water flow actions into one model. The model can be used to estimate the flow of water across and through a final cover. To achieve this, the HELP model uses precipitation and other climatological information to partition rainfall and snow melt into surface runoff, evaporation, and downward infiltration through the barrier layer to the waste.

The HELP model essentially divides a waste management unit into layers, each

Figure 6. Example of a Capillary-Break Final Cover System



Adapted from **<www.hanford.gov/eis/hraeis/eisdoc/graphics/fige-1.gif>**

defined in terms of soil type, which is related to the hydraulic conductivity of each. Users fill in data collection sheets that request specific information on the layers and climate, and this information is input to the model. In performing its calculations, the model will take into account the reported engineering properties of each layer, such as slope, hydraulic conductivity, and rates of evapotranspiration, to estimate the amount of precipitation that can enter the waste unit through the final cover. To use the HELP model properly, refer to the HELP Model *User's Guide* and documentation (U.S. EPA, 1994b; U.S. EPA, 1994c). The model itself, the *User's Guide*, and supporting documentation can be obtained from the U.S. Army Corps of Engineers Web site at **<www.wes.army.mil/el/elmodels>**.

F. Recommended Cover Systems

The recommended final cover systems correspond to a waste management unit's bottom liner system. A unit with a single geomembrane bottom liner system, for example, should include, at a minimum, a single geomembrane in its final cover system unless an evaluation of site-specific conditions can show an equivalent reduction in infiltration. Table 2 summarizes the minium recommend-

Table 2: Minimum Recommended Final Cover Systems*

Type of Bottom Liner	Recommended Cover System Layers (From top layer down)[a]	Thickness (In inches)	Hydraulic Conductivity (In cm/sec)
Double Liner	Surface Layer	12	not applicable
	Drainage Layer	12[b]	1×10^{-2} to 1×10^{-3}
	Geomembrane	30mil(PVC) 60mil (HDPE)	—
	Clay Layer	18	less than 1×10^{-5}
Composite Liner	Surface Layer	12	not applicable
	Drainage Layer	12[b]	1×10^{-2} to 1×10^{-3}
	Geomembrane	30 mil (PVC) 60 mil (HDPE)	—
	Clay Layer	18	less than 1×10^{-5}
Single Clay Liner	Surface Layer	12	not applicable
	Drainage Layer	12[b]	1×10^{-2} to 1×10^{-3}
	Clay Layer	18	less than 1×10^{-7}
Single Clay Liner in an Arid Area	Cobble Layer	2-4	not applicable
	Drainage Layer	12[b]	1×10^{-2} to 1×10^{-3}
	Clay Layer	18	less than 1×10^{-7}
Single Synthetic Liner	Surface Layer	12	not applicable
	Drainage Layer	12[b]	1×10^{-2} to 1×10^{-3}
	Geomembrane	30 mil (PVC) 60 mil (HDPE)	—
	Clay Layer	18	less than 1×10^{-5}
Natural Soil Liner	Earthen Material	24[c]	No more permeable than base soil

* Please consult with your state regulatory agency prior to constructing a final cover.

[a] The final selection of geomembrane type, thickness, and drainage layer requirements for a final cover should be design-based and consultation with your state agency is recommended.

[b] This recommended thickness is for high permeability soil material with at least a 3 percent slope at the bottom of the layer. Some geonet composites, with a minimal thickness of less than 1 inch, have a transmissivity equal to a much thicker layer of aggregate or sand.

[c] Thickness might need to be increased to address freeze/thaw conditions.

ed final cover systems based on the unit's bottom liner system. While the recommended minimum final cover systems include closure layer component thicknesses and hydraulic conductivity, the cover systems can be modified to address site-specific conditions. In addition, you should consider whether to include a protection layer or a gas collection layer. Figures 7 through 11 display recommended minimum final cover systems.

Figure 7. Recommended Final Cover System for a Unit With a Double or Composite Liner

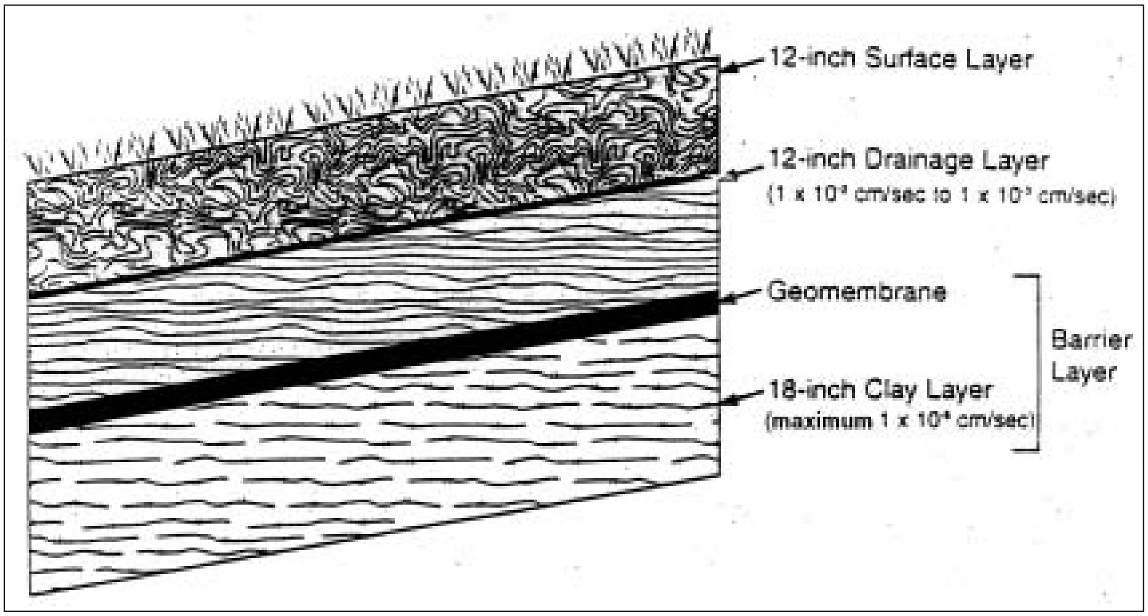


Figure 8. Recommended Final Cover System for a Unit With a Single Clay Liner

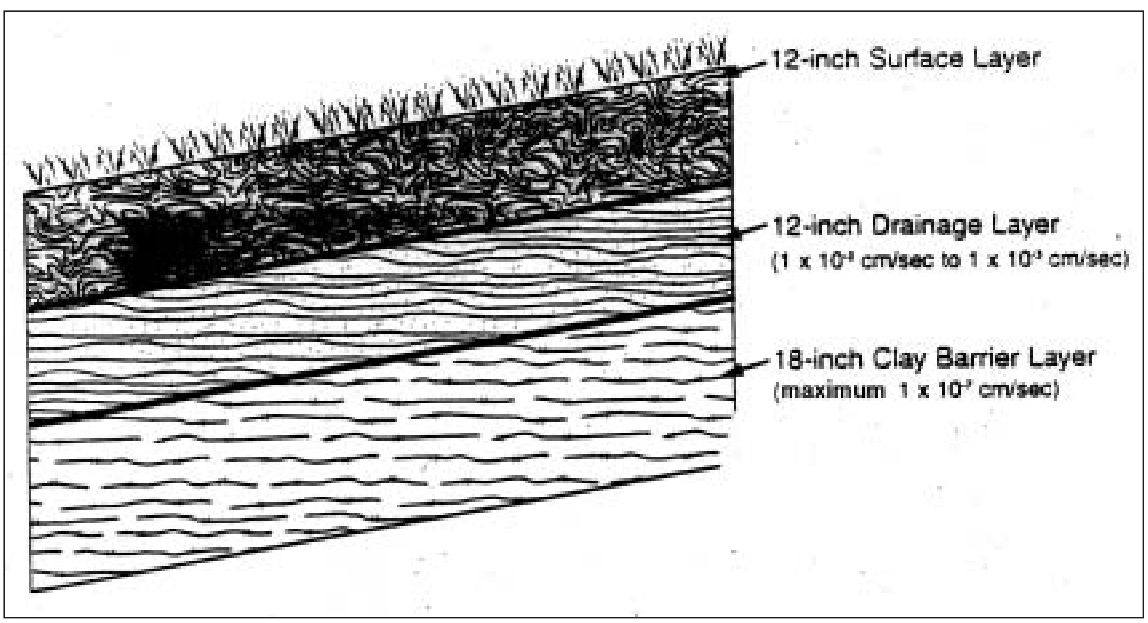


Figure 9. Recommended Final Cover System for a Unit With a Single Clay Liner in an Arid Area

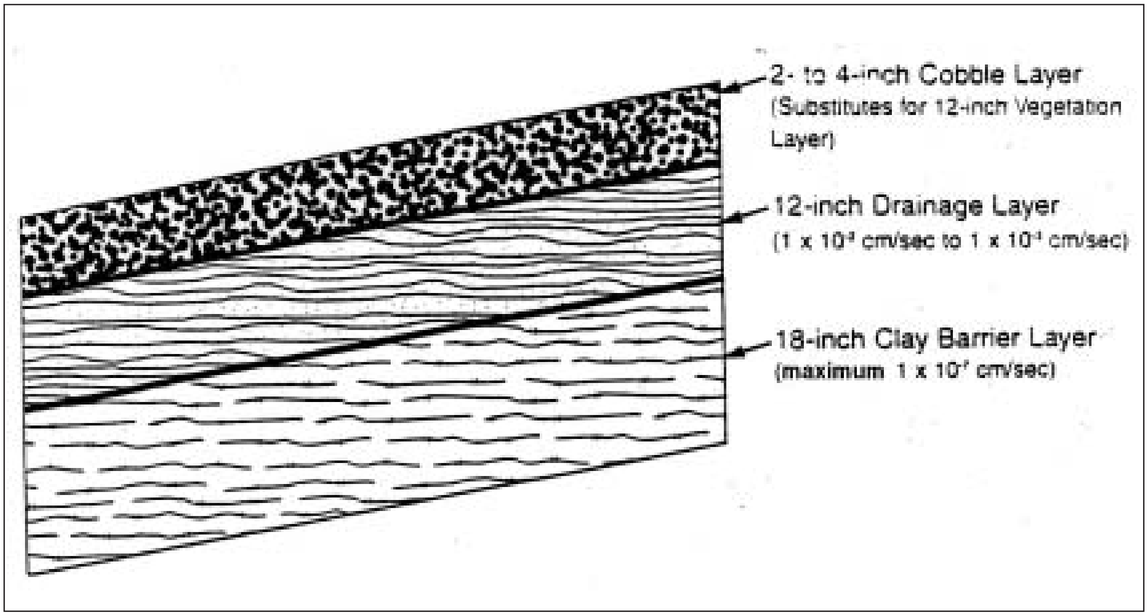


Figure 10. Recommended Final Cover System for a Unit With a Single Synthetic Liner

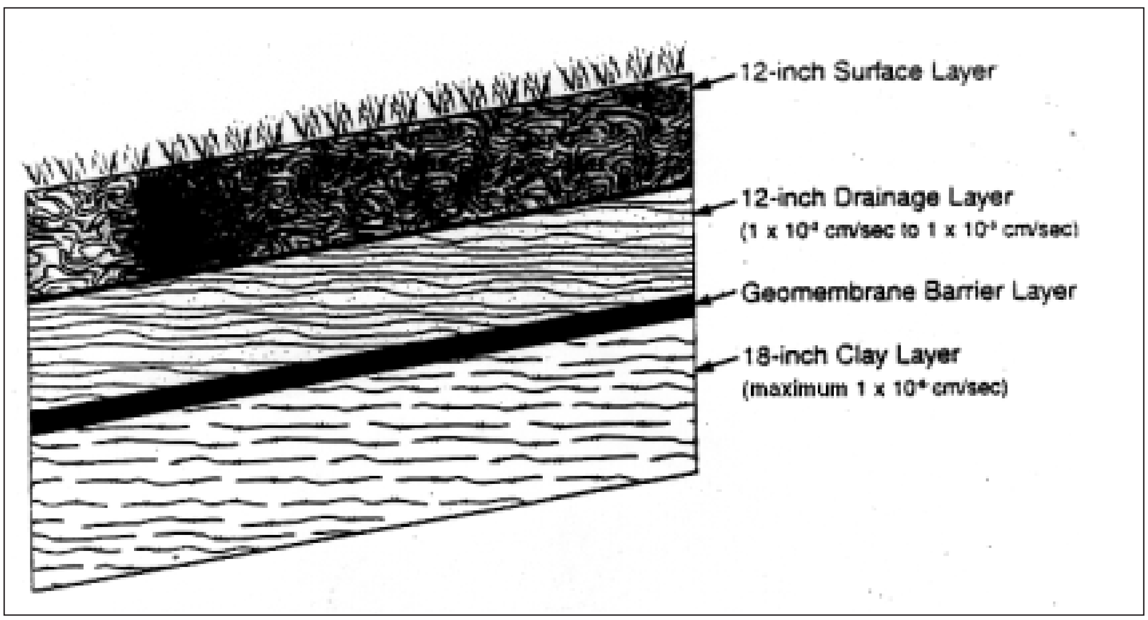
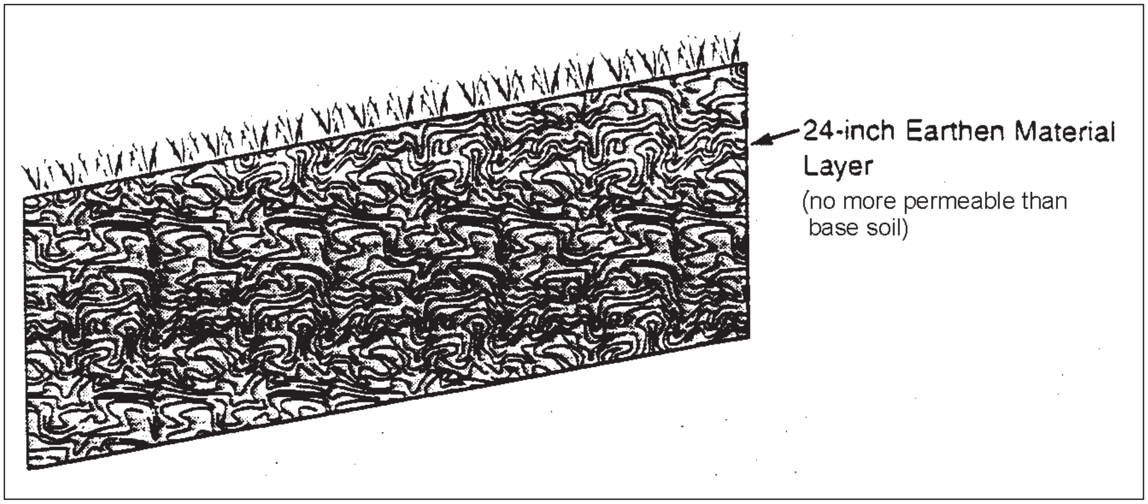


Figure 11. Recommended Final Cover System for a Unit With a Natural Soil Liner



While these recommendations include the use of compacted clay, a facility manager might want to consider the use of a geomembrane barrier layer in addition to, or in place of, a compacted clay barrier layer. Subsidence of a final cover constructed with a compacted clay barrier layer can allow precipitation to enter the closed unit and increase leachate production. The use of a geomembrane in place of compacted clay might be more cost effective. Due to cracking or channeling or continued subsidence, post-closure care of a compacted clay barrier layer can be more expensive to maintain than a geomembrane barrier layer. A geomembrane barrier layer can also accommodate more subsidence without losing its effectiveness.

IV. Closure by Waste Removal

Closure by waste removal is a term that describes the removal and decontamination of all waste, waste residues, contaminated ground water, soils, and containment devices. This approach is common for waste piles and some surface impoundments. Removal and decontamination are complete when the constituent concentrations throughout the unit and any areas affected by releases from the unit do not exceed numeric cleanup levels. You should check with the state agency to see if it has established any numeric cleanup levels or methods for establishing site-specific levels. In the absence of state cleanup levels, metals and organics should be removed to either statistically equivalent background levels or to maximum contaminant levels (MCLs) or health-based numbers (HBNs)[2]. Metals and organics might have different cleanup levels, but they both should be based on either local background levels or on health-based guidelines.

Future land use considerations can also be important in determining the appropriate level of cleanup. One tool that can be used to help evaluate whether waste removal is appropriate at the site is the risk-based corrective action (RBCA) process described in Chapter 10–Taking Corrective Action. The RBCA process provides guidance on integrating ecological and human health risk-based decision-making into the traditional corrective action process.

[2] To learn about the regulatory and technical basis for MCLs, access the Integrated Risk Information System (IRIS), a database of human health effects that can result from exposure to environmental contaminants, at **<www.epa.gov/iris>**. Call the EPA Risk Information Hotline at 513 569-7254 for more information.

A. Establishing Baseline Conditions

A good management practice is to establish the baseline conditions for a waste management unit. Baseline conditions include the background constituent concentrations at a site prior to waste placement operations. Identifying the types of contaminants that might be present can provide an indication of the potential contamination resulting from the operation of a unit and the level of effort and resources that can be required to reach closure. Naturally-occurring elevated background levels that are higher than targeted closure levels might be encountered. In such cases, consult with the state agency to determine whether these elevated background levels are a more appropriate targeted cleanup level. The identification of potential contaminants will also provide a guideline for selecting sampling parameters. If constituents other than those initially identified are discovered through subsequent soil and water sampling, this might indicate that contaminants are migrating from another source.

In some cases, waste contaminants might have been present at a site before a waste management unit was constructed, or they might have migrated to the site from another unrelated source. In these situations, closure by waste removal can still proceed, provided that any contamination originating from the closing unit is removed to appropriate cleanup levels. You should determine whether additional remediation is required under other federal or state laws, such as the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), or state cleanup laws.

How are baseline conditions established?

Initial soil and ground-water sampling around, within, and below a unit will serve to identify baseline conditions. Sampling can detect contaminant levels that exceed background levels or federal, state, or local health-based benchmarks. Contact local environmental protection officials for guidance on the number and type of samples that should be taken. If the initial round of sampling does not reveal any contaminant levels that exceed benchmarks, you should proceed with the removal of waste and the restoration of the unit. If the sampling does reveal contamination that exceeds the benchmarks, you should consider ways to remediate the site in compliance with federal, state, or local requirements.

B. Removal Procedures

Proper removal procedures are vital to the long-term, post-closure care of a unit and surrounding land. Properly removing waste can minimize the need for further maintenance, thereby saving time and money and facilitating reuse of the land. You should perform closure by waste removal in a manner that prevents the escape of waste constituents to the soil, surface water, ground water, and atmosphere. After removing the waste, you should remove all equipment, liners, soils, and any other materials containing waste or waste residues. Removal verification should include specifics as to how it will be determined that residues, equipment, liners, and soils have been removed to baseline conditions. Finally, the land should be returned to the appearance and condition of surrounding land areas to the extent possible consistent with the closure and post-closure plans.

Should a plan for waste removal procedures be prepared?

The waste removal process should be fully described in a closure plan. The removal process description should address estimates of the volumes and types of waste and contaminated equipment or structures to be removed during closure. It should also include the types of equipment to be used, the removal pattern, and the management of loading areas. The closure plan should also detail steps to be taken to minimize and prevent emissions of waste during closure activities. For example, if activities during closure include loading and transporting waste in trucks, the closure plan should describe the steps that will be taken to minimize air emissions from windblown dust. Proper quality assurance and quality control during the waste removal process will help ensure that the removal proceeds in accordance with the waste removal plan. A key component of the waste removal procedure is the consideration of proper disposal or treatment methods for any wastes or contaminated materials.

C. Disposal of Removed Wastes

When a unit is closed by removing waste, waste residues, contaminated ground water, soils, and containment devices, you should ensure that disposal of these materials is in compliance with state law. If the composition of the waste can not be determined using process knowledge, you should test it using procedures such as those described in Chapter 2–Characterizing Waste. Then consult with the state agency to determine which requirements might apply to the waste.

D. Final Sampling and Analysis

The purpose of final sampling and analysis is to ensure that target cleanup levels have been achieved. While initial sampling is intended to establish baseline levels of contaminants, final sampling is used more as a safeguard to make sure levels have not changed. It is important to conduct a final sampling, in addition to the initial sampling, because removal actions can increase the contaminant levels at the site, and sometimes contamination is overlooked in the initial baseline sampling event. Refer to Chapter 9–Monitoring Performance for a detailed discussion of sampling and analysis procedures.

How should the sampling data be used?

The results of this sampling event should be compared to the results of the baseline event, and any discrepancies should be noted. The results can be compared to performance measures established at the beginning of the closure process with state or local regulators. Closure plans incorporating waste removal should include a sampling and analysis plan for the initial and final sampling and analysis efforts. The plan should specify procedures to ensure that sample collection, handling, and analysis will result in data of sufficient quality to plan and evaluate closure activities. The sampling and analysis plan should be designed to define the nature and extent of contamination at, or released from, the closing unit. The level of detail in the sampling and analysis plan should be commensurate with the complexity of conditions at the closing unit.

V. Post-Closure Care Considerations When Final Cover Is Used

For units that will close with a final cover, the following factors should be considered:

- Routine maintenance of the unit's systems, including the final cover, leachate collection and removal systems, run-on and runoff controls, gas and ground-water monitoring systems, and surface-water and gas quality monitoring where appropriate.
- The names and telephone numbers of facility personnel for emergencies.
- Mechanisms to ensure the integrity of the final cover system, such as posted signs or notifications on deeds.
- The anticipated uses of the property during the post-closure period.
- The length of the post-closure care period.
- Costs to implement and conduct post-closure care.
- Conditions that will cause post-closure care to be extended or shortened.

A. Maintenance

After the final cover is installed, some maintenance and repair likely will be necessary to keep the cover in good working condition. Maintenance can include mowing the vegetative cover periodically and reseeding, if necessary. Repair the cover when erosion or subsidence occurs. Maintaining healthy vegetation will ensure the stability of slopes, reduce surface erosion, and reduce leachate production by increasing evapotranspiration. A regular schedule for site inspections of maintenance activities during the post-closure period, as well as prompt repair of any problems found at inspection, can help ensure the proper performance of the cover system. Maintenance of the proper thickness of surface and drainage layers can ensure long-term minimization of leachate production and protection of geomembranes, if present.

What maintenance and repair activities should be conducted after the final cover has been installed?

In the case of damage to the final cover, you should determine the cause of damage so that proper repair measures can be taken to prevent recurrence. For example, if the damage is due to erosion, potential causes might include the length and steepness of slopes, insufficient vegetation growth due to poor planting, or uneven settlement of the waste. Sedimentation basins and drainage swales should be inspected after major storms and repaired or cleaned, as necessary.

Components of the leachate collection and removal system, such as leachate collection pipes, manholes, tanks, and pumps should also receive regular inspection and maintenance. If possible, flush and pressure-clean the collection systems on a regular basis to reduce sediment accumulation and to prevent clogging caused by biological growth. The manholes, tanks, and pumps should be visually inspected at least annually, and valves and manual controls should be exercised even more frequently, because leachate can corrode metallic parts. Repairs will help prevent future problems, such as leachate overflow from a tank due to pump failure.

You should inspect and repair gas and ground-water monitoring wells during the post-closure period. Proper operation of monitoring wells is essential to determine whether releases from a closed waste management unit are occurring. For example, ground-water monitoring wells should be inspected to ensure that they have not been damaged by vehicular traffic or vandalism. Physical scraping or swabbing might be necessary to remove biological clogging or encrustation from calcium carbonate deposits on well screens.

B. Monitoring During Post-Closure Care

Post-closure care monitoring should include the leachate collection system, surface-water controls, the ground-water monitoring system where appropriate, and gas controls where appropriate. Post-closure monitoring will serve as your main source of information about the integrity of the final cover and liners. A reduction in the intensity (i.e., frequency) and scope of monitoring might be warranted after some period of time during post-closure care. Conversely, an increase in intensity and scope might become necessary due to unanticipated problems.

What should be considered when monitoring post-closure leachate, ground water, and gas?

The quantity of leachate generated should be monitored, as this is a good indicator of the performance of the closure system. If the closure system is effective, the amount of leachate generated should decrease over time. In addition, the concentration of contaminants in leachate should, in time, reach an equilibrium. An abrupt decline in the contaminant concentration could mean that the cover has failed, and surface water has entered the waste and diluted the leachate.

To ensure leachate has not contaminated ground-water supplies, you should sample ground water regularly. Regular ground-water monitoring detects changes, or the lack thereof, in the quality of ground water. For a more detailed discussion, consult Chapter 9–Monitoring Performance.

As no cover system is impermeable to gas migration, and if gas production is a concern at the unit, you should install gas monitoring wells around the perimeter of the unit to detect laterally moving gas. If geomembranes are used in a cover, more gas can escape laterally than vertically. Gas collection systems can also become clogged and stop performing properly. Therefore, you should periodically check gas vents and flush and pressure-clean those vents not working properly.

C. Recommended Length of the Post-Closure Care Period

The overall goal of post-closure care is to provide care until wastes no longer present a threat to the environment. Threats to the environment during the post-closure care period can be evaluated using leachate and ground-water monitoring data to determine whether there is a potential for migration of waste constituents at levels that might threaten human health and the environment. Ground-water monitoring data can be compared to drinking water standards or health-based criteria to determine whether a threat exists.

Leachate volumes and constituent concentrations can also be used to show that the unit does not pose a threat to human health and the environment. The threats posed by waste constituents in leachate should be evaluated based on the potential release of leachate to ground and surface waters. Consequently, you should consider doing post-closure care maintenance for as long as that potential exists. Individual post-closure care periods can be long or short depending on the type of waste being managed, the waste management unit, and a variety of site-specific characteristics. You should contact the appropriate state agency to determine what post-closure period it recommends. In the absence of any state guidance on the appropriate length of the post-closure period, consider a minimum of 30 years.

D. Closure and Post-Closure Cost Considerations

The facility manager of a closed industrial unit is responsible for that unit. To ensure long-term protection of the environment, you should account for the costs of closure and post-closure care when making initial plans. There are guidance documents available to help plan for the costs associated with closing a unit. For example, guides produced by the R.S. Means Co. provide up-to-date cost estimates for most construction-related work, such as moving soil, and material and labor for installing piping. Table 3 also presents an example of a closure/post-closure cost estimate form. Table 4 presents a sample summary cost estimating worksheet to assist in determining the cost of closure. Also you should consider obtaining financial assurance mechanisms so that the necessary funds will be available to complete closure and post-closure care activities if necessary. Financial assurance planning encourages internalization of the future costs associated with waste management units and promotes proper design and operating practices, because the costs for closure and post-closure care are often less for units operated in an environmentally protective manner. You should check with the state agency to determine whether financial assurance is required and what types of financial assurance mechanisms might be acceptable.

The amount of financial assurance that might be necessary is based on site-specific estimates of the costs of closure and post-closure care. The estimates should reflect the costs that a third party would incur in conducting closure and post-closure activities. This recommendation ensures adequate funds will be available to hire a third party to carry out necessary activities. You should consider updating the cost estimates annually to account for inflation and whenever changes are made to the closure and post-closure plans. For financial assurance purposes, if a state does not have a regulation or guidance regarding the length of the post-closure care period, 30 years could be used as a planning tool for developing closure and post-closure cost estimates.

Financial assurance mechanisms do not force anyone to immediately provide full funding for closure and post-closure care. Rather, they help to ensure the future availability of such funds. For example, trust funds can be built up gradually during the operating life of a waste management unit. By having an extended "pay-in" period for trust funds, the burden of funding closure and post-closure care will be spread out over the economic life of the unit. Alternatively, consider the use of a corporate financial test or third-party alternative, such as surety bonds, letters of credit, insurance, or guarantees.

What costs can be expected to be associated with the closure of a unit?

The cost of constructing a final cover or achieving closure by waste removal will depend on site-specific activities. You should consider developing written cost estimates before closure procedures begin. For closure by means of a final cover, the cost of constructing the final cover will depend on the complexity of the cover profile, final slope

Table 3: Example Closure/Post-Closure Cost Estimate Form* (All Costs Shown in ($000)

Provisions	Total Closure Costs Yrs. (-)	Total Post-Closure Costs Yrs. (-)	Total Closure/ Post-Closure Costs Yrs. (-)
i Soil Erosion and Sediment Control Plan		NA	
ii Final Cover		NA	
iii Final Cover Vegetation		NA	
iv Maintenance Program for Final Cover and Final Cover Vegetation	NA		
v Maintenance Program for Side Slopes	NA		
vi Run-On and Runoff Control Program		NA	
vii Maintenance Program for Run-On and Runoff Control System	NA		
viii Ground-water Monitoring Wells		NA	
ix Maintenance Program for Ground-water Monitoring Wells	NA		
x Ground-water Monitoring	NA		
xi Methane Gas Venting or Evacuation System		NA	
xii Maintenance Program for Methane Gas Venting or Evacuation System	NA		
xiii Leachate Collection and/or Control System		NA	
xiv Maintenance Program for Leachate Collection and/or Control System	NA		
xv Facility Access Control System		NA	
xvi Maintenance Program for Facility Access Control System	NA		
xvii Measures to Conform the Site to Surrounding Area		NA	
xviii Maintenance Program for Site Conformance Measures	NA		
xix Construction Quality Assurance and Quality Control		NA	
TOTAL COSTS			

* Developed from New Jersey Department of Environmental Protection, Bureau of Landfill Engineering Landfill Permits.

Table 3: Example Closure/Post-Closure Cost Estimate Form (Cont'd)

Provisions	Total Post-Closure Costs	Year #1	Year #2	Year #3	Year #4	Year #5	Year #6	Year #7
i Soil Erosion and Sediment Control Plan	NA							
ii Final Cover	NA							
iii Final Cover Vegetation	NA							
iv Maintenance Program for Final Cover and Final Cover Vegetation								
v Maintenance Program for Side Slopes								
vi Run-On and Runoff Control Program	NA							
vii Maintenance Program for Run-On and Runoff Control System								
viii Ground-water Monitoring Wells	NA							
ix Maintenance Program for Ground-water Monitoring Wells								
x Ground-water Monitoring								
xi Methane Gas Venting or Evacuation System	NA							
xii Maintenance Program for Methane Gas Venting or Evacuation System								
xiii Leachate Collection and/or Control System	NA							
xiv Maintenance Program for Leachate Collection and/or Control System								
xv Facility Access Control System	NA							
xvi Maintenance Program for Facility Access Control System								
xvii Measures to Conform the Site to Surrounding Area	NA							
xviii Maintenance Program for Site Conformance Measures								
xix Construction Quality Assurance and Quality Control	NA							
TOTAL COSTS								

Table 4: Sample Summary Cost Estimating Worksheet

Summary Worksheet for Landfills			
Activity Some of the activities listed below are routine. The owner or operator might elect or be required to conduct additional activities. Italic type denotes worksheets for estimating the costs of those additional activities		Worksheet Number	Cost
1	Installation of Clay Layer	LF-3	$
2	Installation of Geomembrane	LF-4	$
3	Installation of Drainage Layer	LF-5	$
4	Installation of Topsoil	LF-6	$
5	Establishment of Vegetative Cover	LF-7	$
6	*Installation of Colloid Clay Liner*	LF-8	$
7	*Installation of Asphalt Cover*	LF-9	$
8	*Decontamination*	DC-1	$
9	*Sampling and Analysis*	SA-2	$
10	*Monitoring Well Installation*	MW-1	$
11	*Transportation*	TR-1	$
12	*Treatment and Disposal*	TD-1	$
13	**Subtotal of Closure Costs (Add lines 1 through 12)**		
14	Engineering Expenses (Engineering expenses are typically 10% of closure costs, excluding survey plat, certification of closure, and post-closure care.)		$
15	Survey Plat	LF-10	$
16	Certification of Closure	LF-11	$
17	**Subtotal (Add engineering expenses and cost of the survey plat, certification of closure, and post-closure care to closure costs [Add lines 12 through 16])**		$
18	Contingency Allowance (Contingency allowances are typically 20% of closure costs, engineering expenses, cost of survey plat, cost of certification of closure, and post- closure care.)		$
19	Post-Closure Care	PC-1	$
	TOTAL COST OF CLOSURE (Add lines 17, 18, and 19)		**$**

Worksheet generated from CostPro©: Closure and Post-Closure Cost Estimating Software. Available from Steve Jeffords of Tetra Tech EM Inc., 404 225-5514, or 285 Peach Tree Center Avenue, Suite 900, Atlanta, GA, 30303.

contours of the cover, whether the entire unit will be closed (or partial closures), and other site-specific factors. For example, the components of the final cover system, such as a gas-vent layer or a biotic layer, will affect costs. In addition, closure-cost estimates would also include final-cover vegetation, run-on and runoff control systems, leachate collection and removal systems, ground-water monitoring wells, gas-monitoring systems and controls, and access controls, such as fences or signs. Closure costs might also include construction quality assurance costs, engineering fees, accounting and banking fees, insurance, permit fees, legal fees, and, where appropriate, contingencies for cost overruns, reworks, emergencies, and unforeseen expenses.

For closure by means of waste removal, closure costs would include the costs of removal procedures, decontamination procedures, and sampling and analysis. Closure cost estimates should also consider the costs for equipment to remove all waste, transport it to another waste management unit, and properly treat or dispose of it. In addition, fugitive dust emission controls, such as dust suppression practices, might need to be included as a closure cost. Table 5 presents example estimates of average closure costs for typical closure activities. It also presents estimates of typical post-closure care costs discussed in more detail below.

What costs can be expected to be associated with post-closure care?

After a waste management unit is closed, you should conduct monitoring and maintenance to ensure that the closed unit remains secure and stable. Consider the costs to conduct post-closure care and monitoring for some period of time, such as 30 years (in the absence of a state regulation or guidance). If a unit is successfully closed by means of waste removal, no post-closure care costs would be expected. Post-closure care costs should include both annual costs, such as monitoring, and periodic costs, such as cap or monitoring well replacement.

For units closed by means of a final cover, you should consider the costs for a maintenance program for the final cover and associated vegetation. The more frequent the timing of the maintenance activities, the greater your post-closure care costs will be. This program might include repair of damaged or stressed vegetation, and maintenance of side slopes. Costs to maintain the run-on and runoff control systems, leachate collection and removal systems, and ground-water and gas monitoring wells should also be expected. In addition, sampling, analysis, and reporting costs should be factored into the post-closure cost estimates. See Table 5 above for estimates of post-closure care costs.

Post-closure costs should be updated annually as a record of actual unit costs is developed. Some costs, such as erosion control and ground-water sampling, might be reduced over time as the vegetation on the cover matures and a meaningful amount of monitoring data is accumulated. Due to site-specific conditions, a shorter or longer post-closure period might be determined to be appropriate.

How can long-term financial assurance for a unit be obtained?

Different examples of financial assurance mechanisms include trust funds, surety bond, insurance, guarantee, corporate guarantees, and financial tests. Trust funds are a method whereby cash, liquid assets, certificates of deposit, or government securities are deposited into a fund controlled by a trustee, or state agency. The trust fund amount should be such that the principal plus accumulated earnings over the projected life of the waste management unit would be sufficient to pay closure

Table 5. Example Estimated Closure and Post-Closure Care Costs

Closure Activity	Cost Estimate
Estimated average total landfill closure cost	$4,000,000 [1]
Complete site grading	$1,222/acre [2]
Landfill capping	
Total (all capping materials & activities)	$80,000 – $100,000/ acre [3]
Compacted clay cap	$5.17/cubic yard of clay [2]
Geosynthetic clay liner cap	$16,553/acre [2]
Leachate collection and treatment	$0.05 – $0.15/gallon [3] $0.25/gallon [2]
Reclamation of area (applying 2.5 feet of top soil and seeding)	$10,200/acre [3]
Install ground-water monitoring wells	$2,400/well [4]
Install methane monitoring wells (if applicable)	$1,300/well [4]
Install perimeter fence	$13/linear foot [4]
Repair/replace perimeter fence	$2.20/linear foot [2]
Construct surface-water structures	$1/linear foot [4]

Post-Closure Activity (based on 30 year post-closure care period)	Cost Estimate
Estimated average total landfill post-closure care cost	$1,000,000 [1]
Conduct annual inspections	$22,000/facility/year [4] $15,000/facility/year [2]
Maintain leachate collection systems	$60,000 [2]
Conduct Post-closure ground-water monitoring (sampling and analysis)	$15,000 – $25,000/year [3] $12,000/well [4]
Conduct methane monitoring	$7,200/well [4]
Maintain perimeter fence	$12/linear foot [4]
Maintain surface-water structures	$1/linear foot [4]
Remove perimeter fence (at end of post-closure care period)	$2/linear foot [4]

[1] ICF Incorporated. Memo to Dale Ruhter, September 11, 1996

ICF's data show that total closure and post-closure care costs are dependent upon the size of the landfill. The size ranges and corresponding cost estimates were used to calculate the estimated average total costs.

Notes for Table 5

Subtitle D Landfill Closure Costs

Size Range (tons per day)	Cost (in 2000 dollars)
50 – 125	$2,700,000
126 – 275	$5,100,000
276 – 563	$8,300,000
564 – 1125	$11,800,000

Subtitle D Landfill Post-Closure Care Costs

Size Range (tons per day)	Cost (in 2000 dollars)
50 – 125	$820,000
126 – 275	$980,000
276 – 563	$1,400,000
564 – 1125	$1,700,000

[2] Oklahoma Department of Environmental Quality. Table 5.2 Closure Cost Estimate and Table 5.3 Post Closure Estimate from Chapter 5 of Solid Waste Financial Assurance Program Report. December 2000.

[3] Jeffrey H. Heath "Landfill Closures: Balancing Environmental Protection with Cost," MSW Management. January/February 1996. pp. 66-70.

[4] Wyoming Department of Environmental Quality, Solid and Hazardous Waste Division. Solid Waste Guideline #12: Participation in the State Trust Account. May 1994.

and post-closure care costs. Surety bond, insurance, and guarantee are methods to arrange for a third party to guarantee payment for closure and post-closure activities if necessary. A financial test is a standard, such as an accounting ratio, net worth, bond rating, or a combination of these standards, that measures the financial strength of a firm. By passing a financial test, it is determined that one has the financial strength to pay for closure and post-closure costs.

A more detailed explanation of these examples and other potential financial assurance mechanisms is provided below. These mechanisms can be used individually or in combination. This Guide, however, does not recommend specific, acceptable, financial assurance mechanisms.

- **Trust funds.** A trust fund is an arrangement in which one party, the grantor, transfers cash, liquid assets, certificates of deposit, or government securities into a fund controlled by a special "custodian," the trustee, who manages the money for the benefit of one or more beneficiaries. The trust fund should be dedicated to closure and post-closure care activities. Payments are made annually into the fund so that the full amount for closure and post-closure care accumulates before closure and post-closure care activities start. A copy of the trust agreement, which describes how the funds will be used to pay for closure and post-closure care activities, should be placed in the waste management unit's operating record.
- **Surety bond.** A surety bond guarantees performance of an obligation, such as closure and post-closure care. A surety company is an entity that agrees to answer for the debt or default of another. Payment or performance surety bonds are acceptable in the event an owner or operator fails to conduct closure and post-closure care activities. If you use a surety bond or letter of credit, you should establish a standby trust fund (essentially the same as a trust fund).

In most cases, a standby trust fund is established with an initial nominal fee agreed to by the owner or the operator and the trustee. Further payments into this fund are not required until the standby trust is funded by a surety company. The surety company should be listed as an acceptable surety in Circular 570 of the U.S. Department of Treasury.

- **Letters of credit.** A letter of credit is a formalized line of credit from a bank or another institution on behalf of an owner or operator. This agreement states that it will make available to a beneficiary, such as a state, a specific sum of money during a specific time period. The letter of credit should be irrevocable and issued for 1 year. The letter of credit should also establish a standby trust fund.
- **Insurance.** An insurance policy is basically a contract through which one party guarantees another party monies, usually a prescribed amount, to perform the closure or post-closure care in return for premiums paid. The policy should be issued for a face amount at least equal to the current cost estimate for closure and post-closure care. The face amount refers to the total amount the insurer is obligated to pay; actual payments do not change the face amount.
- **Corporate financial test.** Corporate financial tests are a method for an owner and operator to self-guarantee that they have the financial resources to pay for closure and post-closure costs. These tests might require that a company meet a specified net worth, a specified ratio of total liabilities to net worth, and a specified net working capital in the United States. Implicit in using a financial test is a reliance on Generally Accepted Accounting Principles (GAAP) to provide fairly represented accounting data. Your financial statements should be audited by an independent certified public accountant. If the accountant gives an adverse opinion or a disclaimer of opinion of the financial statements, you should use a different financial assurance mechanism.
- **Corporate guarantee.** Under a corporate guarantee, a parent company guarantees to pay for closure and post-closure care, if necessary. The parent company should pass a financial test to show that it has adequate financial strength to provide the guarantee. A financial test is a way for guarantors to use financial data to show that their resources are adequate to meet closure and post-closure care costs. The guarantee should only be used by firms with adequate financial strength.
- **Other financial assurance mechanisms.** If you consider other financial assurance mechanisms, you should talk to your state to see if the mechanism is acceptable.

Performing Closure and Post-Closure Care Activity List

You should consider the following while developing closure and post-closure care activities for industrial waste management units.

- ❑ Develop a closure and post-closure plan, specifying the activities, unit type, waste type, and schedule of the closure.
- ❑ If using a final cover to accomplish closure:
  - — Include the specifications for the final cover in the closure plan.
  - — Determine whether the waste will need stabilization or solidification prior to constructing the final cover.
  - — Address site-specific factors that can affect cover performance.
  - — Select the appropriate materials to use for each layer of the final cover.
  - — Evaluate the effectiveness of the final cover design using an appropriate methodology or modeling program.
  - — Establish a maintenance plan for the cover system.
  - — Establish a program for monitoring the leachate collection system, ground-water quality, and gas generation during the post-closure period.
  - — Ensure proper quality assurance and quality control during final cover installation and post-closure monitoring.
- ❑ If accomplishing closure by waste removal:
  - — Include estimates of the waste volume, contaminated soils and containment structures to be removed during closure.
  - — Establish baseline conditions and check to see if the state requires numeric cleanup levels.
  - — Develop removal procedures.
  - — Develop a sampling and analysis plan.
  - — Ensure proper quality assurance and quality control during sampling.
- ❑ Determine what post-closure activities will be appropriate at the site.
- ❑ Estimate the costs of closure and post-closure care activities and consider financial assurance mechanisms to help plan for these future costs.

Resources

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